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UNSTEADY GAS DYNAMICS PROBLEMS RELATED TO FLIGHT VEHICLES

BY
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Report summarizes the findings of a five-year program devoted to improving fundamental knowledge on unsteady aerodynamic phenomena related to flight vehicles and on associated aeroelastic problems. Principal areas of activity and representative discoveries made under them are listed. With regard to minimum-weight structural optimization with aeroelastic constraints, both new results and new methods of solution for free and forced motion were published. The effect of chordwise-force components on flutter of large-

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aspect-ratio wings proved often to be unfavorable. Improved steady and unsteady theories were published for the loading of vertical-axis wind turbines, and discoveries were made regarding free vibration of their curved blades. It was learned how to adapt linearized theory for simple harmonic oscillation to cover arbitrary small motion, with applications to automatic control. A nonlinear approach was published for transient lifting airloads at low speeds. A study was undertaken on aerodynamics useful for the analysis of variable-geometry propulsive devices. An approximate scheme was devised for highlighting the importance of partial-chord shocks for transonic aeroelastic stability, their influence proving often large and unfavorable. Among and in addition to listed project publications, two survey papers, numerous seminars and talks communicated various of these findings.

Research Objectives

The overall objective of the five-year program has been to improve fundamental knowledge on unsteady aerodynamic phenomena related to flight vehicles and on associated aeroelastic problems. The results are believed to have practical utility because many atmospheric cruising aircraft of importance to USAF, both fixed and rotary-wing, are still subject to penalties in performance and airframe weight because of correctible limitations imposed by aeroelastic instability and response.

The principal topics which have been investigated provide a convenient framework upon which to structure the sections of this report. They are as follows:

- Potential flow about three-dimensional, streamlined, lifting configurations, with application to wings and rotors.
- Minimum-weight structural optimization with aeroelastic and structural-dynamic constraints.
- Chordwise aerodynamic forces and their role in aeroelastic stability.
- Unsteady aerodynamic and aeroelastic phenomena related to wind turbines and similar devices.
- Airloads for arbitrary time-dependent motion, with special reference to the automatic control of aeroelastic behavior.
- Other studies on unsteady compressible and hypersonic flows.

Potential Flow about Three-Dimensional, Streamlined, Lifting Configurations with Application to Wings and Rotors

A numerical method has been developed and successfully applied which is believed capable of converging to the exact calculation of three-dimensional lifting potential flows, including cases of unsteady motion. Tbe exact body surface boundary conditions are enforced, and all wake surfaces are unconstrained — allowed to move with the local velocity field. The assumptions made in the theoretical model are that the fluid is ideal (incompressible and inviscid) and that no separation may take place.

The basic solution consists of the Green's function approach, where the velocity potential at any point in the fluid is represented by a continuous distribution of doublets of unknown strength on each of the bounding surfaces. Application of the surface tangency condition yields a set of coupled, singular Fredholm integral equations of the first kind relating the velocity potential doublet distributions to the normal velocity on the body surfaces and subject to the Kutta-Joukowski condition at trailing edges and the dynamic and geometric free surface conditions on all wakes.

An algorithm was constructed for the specific application of the method to isolated wings in translational motion and to propellers or rotors in combined rotational and axial motion. The numerical solution was obtained in a step-by-step fashion. All configurations were impulsively started from rest, and body

geometries ranged from simple zero thickness planforms to a swept tapered wing of finite thickness. The surface integrals were evaluated by means of a discrete set of approximate quadrilateral surface elements, and a "step" doublet distribution over each of the elements was assumed. Successful prediction of surface pressure distribution, indicial circulation, and indicial lift (thrust) is demonstrated, and the effects of thickness and taper as well as the shedding direction are discussed. In the propeller or rotor case, the indicial thrust and circulation are shown to overshoot shortly after motion starts and then approach asymptotically from above their steady-state values. This is caused by induction from wakes shed from forerunning blades. Finally, the roll-up of the starting vortex behind a three-dimensional wing of finite thickness at high angle of attack was successfully predicted. The modeling of the distorted rotor wake geometry was, however, partially successful. Initial roll-up and contraction were properly modeled, but an irregularity developed in the tip vortex due to the presence of wake surfaces from other blades.

The main limitation on producing results by this methodology involved computer capacity and cost, since no serious difficulty with convergence or instability arose in most applications. This investigation is complete and formed the Ph.D. Dissertation of Dr. J.M. Summa. It built on earlier AFOSR-sponsored research by the Principal Investigator, which resulted in publications such as Djojodihardjo and Widnall (Ref. R1)*. Dr. Summa's own published papers in this area are Refs. 1 and 2.

Minimum-Weight Structural Optimization with Aeroelastic and Structural Dynamic Constraints

This long-term program of research — partially supported by AFOSR with the collaboration of USAF Flight Dynamics Laboratory and NASA Langley Research Center — is now essentially complete as far as Stanford's interest is concerned. Under different sponsorship, however, there are plans for a revival, because of the topic's significance for maximum structural efficiency and reduced aircraft fuel consumption.

Starting with Ref. R2, the Stanford group was first concerned with the search of function space for optimized continuous structures. Johnson et al. (Ref. 3) is the most recent archive publication to emerge from this thread of investigation. In parallel and more recently a second focus was on more realistic discrete structures — represented, for example, by finite-element approximations. Of three papers (Ref. 3,4,5) delivered at the AIAA/ASME/SAE 17th SDM Conference, two derive wholly from Stanford's activity and the third was an immediate offshoot of Segenreich's thesis. In response to several demands, it was decided in 1976 to distribute a comprehensive SUDAAR (Ref. R3), reproducing in extenso the related dissertations by Segenreich, Johnson and Rizzi.

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* In accordance with instructions, the list of references is split into 1.) publications from the project in archive journals or similar refereed proceedings and 2.) other cited material (identified with prefix R). Ph.D. Dissertations are cited in the list of professional personnel.

Reference 3 is really a fundamental study in applied mechanics but with practical implications. Its problem is to find the cantilever bar or thin torsional rod of minimum weight under sinusoidal excitation from the free end, with constraints on allowable stress amplitude and on minimum gauge. This case was shown to involve a denumerable infinity of feasible regions in design space, each with an optimal solution. For the first time on a continuous system, these solutions have been mapped out completely and computed accurately in the lower range of forcing frequencies. The need to add tip inertia, in order to obtain meaningful results under certain conditions, was identified. This application also constitutes the most difficult structural-dynamic example to date (1975) of transfer of methodology from the field of optimal control theory. It is believed that the way has been pointed for more practical applications in the future.

The three theses in Ref. R3 deal mainly with discrete aeronautical structures, typically approximated by finite element models. Following on and improving the approach begun at Stanford (e.g. Gwin & McIntosh, Ref. R4), Seigenreich perfected a mathematical programming method for designing light-weight lifting surfaces with constrained speed and altitude of flutter instability. It was successfully used on examples with up to 90 design variables. (The B-1 horizontal stabilizer was, incidentally, sized over most of its area by a simplified scheme having this same objective.)

Johnson's focus was on the less-explored area of forced response. His most elaborate example dealt with fracture mechanics, as applied to determine a minimum-weight elastic wing subjected to stationary random atmospheric turbulence. But he also studied several cases with simple harmonic forcing.

Finally, Rizzi adapted and refined an optimality criterion due to Kiusalaas. He first showed how it efficiently reproduces a number of minimum-weight structural designs under static loading, which had previously been published elsewhere. He then demonstrated his method to be probably the fastest, most accurate way of applying aeroelastic constraints to multi-degree-of-freedom systems.

<u>Chordwise Aerodynamic Forces and Their Role in Aeroelastic Stability and Variable-Geometry Propulsive Flight</u>.

This topic has been extensively studied throughout the five years, with recent emphasis on improving the accuracy and realism of earlier analyses of the influence of chordwise aerodynamic forces and the chordwise bending degree of freedom on flexure-torsion flutter of a cantilever surface of moderate to large aspect ratio. This builds on an initial study by Petre of the static divergence problem, which led, with partial AFOSR support, to the first publication (Ref. 6) dealing with <u>dynamic</u> aeroelastic stability. Although based on a simplified model with incompressible, strip-theory aerodynamics and a fixed direction for the uniform drag load, Ref. 1 contains some interesting discoveries. For instance, at quite high aspect ratios when the parameter $C_D\ [dc_L/d\alpha]^{-1}$ takes values around 0.02, there is predicted more than a 15% reduction in flutter dynamic pressure relative to the same wing with drag neglected.

Since these conditions are representative both of high-performance sailplanes and of certain RPV's with potential military applications, further investigation was deemed desirable. The recent Ref. 7 extends the model to include "follower" drag forces.

The work has taken two directions: 1) A search for experimental confirmation and 2) more sophisticated theory. The former was relatively unsuccessful. Although a number of relevant tests have been found, of which the series described by Theodorsen and Garrick (Ref. R5) is probably the best example, they suffer from one or both of two difficulties. Either the aspect-ratio parameter was so small that an unfavorable drag effect on flutter is not predicted, or the expected errors in the reported flutter speed and frequency are so large that the change due to drag is not discriminated. A further disappointment was that these large, flimsy models were usually suspended vertically at zero-mean lift. As will be mentioned below, there is an especially important influence of the bending deformation due to mean lift, but available wind-tunnel data do not contain it. Such lift is always present in cruising flight.

The research group remains convinced, however, that the drag influence is both real and potentially important. In part, this belief is grounded in the more rigorous analyses reported in the Ph.D. dissertation by Dr. William Boyd. A paper based thereon (Ref. 8) was presented by Dr. Boyd at the most recent AIAA SDM Conference, and submission is made for regular publication in J. Aircraft. Reference R14 summarizes early related studies.

During the process of obtaining solutions for neutral dynamic stability at nonzero steady lifting conditions using this method, a certain awkardness of the simple harmonic approach, the V-g method familiar to aeroelasticians, became evident. Flutter speed for a given configuration first had to be estimated so that steady deflections could be calculated, and then the dynamic eigenvalue problem had to be solved to obtain a corresponding flutter condition. Several interactions of this procedure were needed to match the estimated and calculated flutter speeds.

This and other factors led to a different approach to the treatment of time dependence for the stability analysis. The Laplace transform in time was taken, and the stability of the true aeroelastic modes of the system determined by examining the zeroes of its determinant. This approach of course requires that the aerodynamic loads be expressible for arbitrary unsteady motion in time. Work by Edwards (see below) in this area for two-dimensional unsteady incompressible aerodynamics was of great assistance. The need to estimate beforehand the flutter speed was avoided, and the true aeroelastic stability of the wing at any flight speed and lifting condition can easily be displayed by the roots locus technique.

Extensive calculations were carried out using incompressible strip-theory for wings of various configurations at lifting conditions. In addition, the first-order effects of the unsteady propulsive force arising from leading edge suction were included. Conclusions which can be drawn include the following:

1. Large-aspect-ratio wings uniformly display a reduction in flutter speed when steady-state deformations are introduced.
2. The ratio of horizontal bending stiffness to vertical bending stiffness is significant in the flutter behavior of large-aspect-ratio cases.
3. The effect of uniform drag on flutter at zero steady lift is insensitive to lifting conditions.
4. Unsteady propulsive forces are stabilizing and become noticeable at high lift conditions.

A significant final phase of Boyd's research was the introduction of three-dimensional, compressible aerodynamic theory for predicting the potential flow portions of the required airloads. An accurate computer program due to Rowe et al. (Ref. R6) has been modified for this purpose. With this program now available as a routine tool, it is appropriate to examine other ways it can contribute to the goals of this project. Unsteady flow effects have thus far, for the most part, been tolerated instead of appreciated despite the oft-expressed interest in ornithopter propulsion and the like. While the analytical treatment of unsteady lift is well developed, the analysis of the unsteady propulsive forces produced by beating wings is incomplete.

Therefore, the progress of present theories towards predicting the propulsive flight of variable-geometry devices like birds and ornithopters has been assessed. The effects of parameters neglected in these theories (viscosity, interference, large amplitude motion, compressibility) are being estimated, and the possibilities of adapting flapping wing propulsion to flight vehicles, including some with potential military significance, are being investigated.

This work is being coordinated very closely with the literature search, wind-tunnel measurements, etc. now being supported at Stanford by AFFDL and AFOSR under Contract No. 77-3263. To this end, the Research Assistantship and other expenses of graduate student James Nathman are funded partly from each contract.

In two-dimensional flow, preparations have been made under Contract No. 77-3263 to correlate the theory with measurements focussed on the chordwise and leading-edge-suction components of the unsteady loading. This will be done on an existing, high-fidelity model mounted in the Stanford 0.5-meter low-speed wind tunnel.

The first step towards understanding propulsive flight and to prepare for these tests was to extend Garrick's work (Ref. R7) and use it to support the two-dimensional wind-tunnel tests. An expansion of Garrick's analysis was required, since he only calculated the mean thrust of the 2-D airfoil. The oscillatory forces and moments have been determined, and provision has been made for net lift. These were programmed for the Stanford IBM 370/168, and the extensive calculations needed for a special wind-tunnel report were made.

Some conclusions, based on these calculations, are:

1. Natural flight is characterized by the most efficient production of thrust, rather than for maximum propulsive efficiency.
2. This also corresponds to a minimum of the oscillatory forces.
3. When amplitude-limited, other motions can produce more thrust.
4. When stall limited, natural-flight motion will produce the maximum thrust.

Analytical forms for maximizing thrust have been developed, and these will also be obtained for maximizing efficiency.

The work of Wu (Ref. R8) has been mechanized to study the effects of oscillatory camber. No significant contribution to the thrust has been noted for physically realistic values of camber. Rather it appears that cambering is important in shaping the pressure distribution on the airfoil. This becomes significant for preventing stall. Also by restricting the motions to physically realistic ones, the dilemma of an infinite number of optimum shapes is removed. The validity of these conclusions drawn from two-dimensional data is being tested by simulating the flight of a dragonfly with the lifting-surface theory of Ref. R6.

Unsteady Aerodynamic and Aeroelastic Phenomena Related to Wind Turbines and Similar Devices.

Considerable progress has been made in dealing with aerodynamics, vibration and aeroelastic problems of vertical-axis wind turbines typified by the Darrieus machine (see Chap. 4, Ref. R9, and R10). When configured in the zero-bending-moment Troposkien shape, such devices promise to attain outstanding low weight per unit of power generated. But they are clearly susceptible to severe problems of aeroelastic response, static and dynamic stability. Related phenomena could arise in rotary-wing aeronautical systems.

As a preliminary to research in these areas, the aerodynamics of the Darrieus were thoroughly reviewed. Existing quasi-steady theory was reproduced for operation at $\omega R/V_w$ and extended to include realistically the losses due to profile and induced drag. Then unsteady effects were predicted on the instantaneous and average values of rotor torque and streamwise force — first by adapting old solutions. Comparisons were made with existing data such as Blackwell *et al.* (Ref. R10). This research was summarized in a paper by the Principal Investigator (Ref. 9). One interesting finding — as yet unconfirmed experimentally — is that unsteady influences even at very low reduced frequency (0.03 - 0.05 are typical) are predicted to cause 10-15% reductions in the power extracted by a lightly-loaded wind turbine. More complicated unsteady effects are still under study.

A parallel program on free vibrations of the vertical-axis machine was conducted in response to the invitation to prepare Ref. 10. In dealing with this extremely complicated phenomenon, a collaboration was developed with Prof. Charles Steele of Stanford University, who is a recognized authority in the field of asymptotic methods for determining eigenvalues and eigenfunctions. It appears that this approach is the most promising one for dealing practically with the phenomena of free vibration and flutter (**cf.** Steele, Ref. R11).

A Ph.D. candidate K. Barry, working with Steele and the Principal Investigator, has been successful in its efficient adaptation to vibration of uniform beams cantilever from a rotating outer or inner hub (a four-state system). For the curved Troposkien blade, equations of motion have been derived for the case of infinite torsional rigidity and reduced to state-vector form (ten states).

It appears, however, that torsion plays a large part in determining aeroelastic stability. Accordingly, the question was examined of adding these degrees of freedom. It leads to a total of 12 states, even in the linear approximation. A parallel question is whether certain nonlinear couplings, associated with the boundary conditions, between torsion and bending must be

taken into account. If so, a limit-cycle type of situation will replace classical flutter. Ph.D. candidate Fred Nitsche recently joined the investigations in this area. His subject is aeroelastic stability and free vibration of the full Troposkien blade.

Airloads for Arbitrary Time-Dependent Motion.

This subject remains a major interest of the Principal Investigator. His attention to it and related issues in unsteady aerodynamic theory was concentrated by an invitation to deliver a major survey paper (Ref. 11) at a meeting of the AGARD Fluid Dynamics Panel. Space does not allow repeating the conclusions or several new findings contained in this review. Two are perhaps worth listing:

1) Theoretical methods for predicting oscillatory airloads on isolated, planar, 3-D lifting surfaces in subsonic or supersonic flight appear to have reached such a level of development that they may normally be used with confidence in a converged accuracy of a very few percent. The same is not true, however, of methods for interfering surfaces.

2) The transonic range still poses an insuperable challenge to the general application of classic linearized theory. The promise of nonlinear computational fluid dynamics is such that, when effects of separated flow can be neglected,

The emphasis of work under the subject grant was aerodynamic generalized forces for arbitrary, small, time-dependent motions in potential flow. Accurate predictions of these — as contrasted with theory for purely simple harmonic motion, which dominates the literature — are an essential tool for the design of automatic control systems to improve aeroelastic performance. Studies built on the pioneering research of Vepa (Ref. 12), and especially the doctoral thesis of Edwards (published as Edwards, Ashley and Breakwell, Ref. 13). Recently the control theorist Balakrishnian (Ref. R12), was thereby stimulated to examine aeroelastic systems as examples of "infinite state" systems in Hilbert space. It is believed that his efforts, which characterize the aeroelastic plant as something unique from the automatic control standpoint, will both improve basic understanding and bring a modern field of mathematics closer to practical application. (It is noted that both Vepa's and Edwards' research was partly supported under the subject AFOSR grant.)

It has been demonstrated that several existing 2-D and 3-D aerodynamic codes for planar wings can be adapted to arbitrary motion in accordance with Edwards' conjecture. The methodology is clearly extendable to any unsteady flow situation governed by the familiar linearized differential equations. An important theoretical question has been settled, which remained uncertain at the time of preparation of Ref. 13. This had to do with whether the so-called "initial-conditional potential" (referred to as $\bar{\Phi}_2$ in the Laplace-transform domain must be included when calculating such "aerodynamic indicial functions" as the classical Wagner function. It has now been proved that $\bar{\Phi}_1$ is adequate for these purposes, except that tables or computations of this and related quantities for very high reduced frequencies are needed in order to reproduce the correct behavior.

Both Edwards and the Principal Investigator spent considerable time colloborating with engineers from various airframe manufacturers toward adaptation of existing linearized-theory computer codes so as to cover arbitrary small motions of wings. For example, several meetings were held during 1977, '78 and '79 with W.S. Rowe, The Boeing Co., relative to his methods published in Ref. R6 and more recent reports. After several unpromising approaches were rejected, a scheme was found that will lead to an effecient generalization of the "RHO" codes. Programming is expected to be completed during Summer 1979.

Another topic which has undergone preliminary investigation is the adaptation of available high-Reynolds-number codes from computational fluid dynamics to aeroelastic phenomena — particularly in the transonic flight speed range. In this connection, a recent seminar (Ref. R13) presented by the Principal Investigator was received with considerable interest and comment.

Finally, results of this work and other activity under the grant were described in an invited lecture before the Israel Society of Aeronautics and Astronautics, published as Ref. 14.

Other Studies in Unsteady Compressible and Hypersonic Flows.

The invited survey papers (Refs. 11 and 14), in addition to reviewing a wide variety of recent developments in the subject field, contained summaries of investigations under this grant. Certain of these were not mentioned in the preceding sections because they go beyond the classical linearized unsteady theory which has been almost universally the aeroelastician's tool.

Although it remains a continuing interest, little is set down here about unsteady hypersonic flow. It constitutes a rather thoroughly explored field. Although new contributions were sought throughout the five years, nothing deserving of publication has as yet emerged. Study of the subject will not, however, be discontinued.

Much more relevant and uncertain today is unsteady transonic flow, particularly for airloads in circumstances where shock waves are located partway back along the airfoil's upper and/or lower surfaces. Finite-difference solutions are believed to hold the best promise for ultimate prediction of unsteady transonic phenomena, but only in two dimensions has any significant accomplishment been reported to date (see Ref. 15 for a summary of the relevant literature). Accordingly, a more approximate but very computationally efficient model was developed to simulate the shocks' effects. Reference 15 was the first publication from this investigation.

The selected idealization consists of superimposing concentrated shock airloads upon distributed pressures taken from subsonic linearized theory. This was guided by the discussion of shock oscillations and the data of Tijdeman (Ref. R17). For small airfoil motions, the shock was found to apply a nearly simple harmonic force with a very large phase lag even at low reduced frequencies. "Universal curves" were estimated for the force amplitude and phase.

Reference 15 presented a number of examples of shock influences on aeroelastic stability. For instance, the necessary condition for neutral stability of pure pitching oscillation by an airfoil is that the out-of-phase component of the pitching moment must vanish. In the parameter range of greatest importance, a 100% increase in the upper reduced-frequency limit for such instability of an 18%-thick biconvex airfoil at Mach 0.781 takes place when the shock is superimposed on the classical aerodynamic model.

Many similar calculations were presented in Ref. 15, the majority dealing with simulated flexure-torsion flutter. In numerous instances, 25-50% changes in flutter speed occur as a result of the shock. The changes may be favorable or unfavorable, the direction being impossible to predict in advance for a given system. It is believed that the explanation has been found for several recent flutter incidents that were unanticipated. It was also determined that flutter clearance of a "supercritical" transonic wing cannot be achieved merely in the vicinity of its design point, since very unfavorable consequences may occur from moving a few hundredths in Mach No. or tenths in lift coefficient away from that point.

During the last few months of the subject program, an interesting study was initiated on the so-called "mass flux" approach for transonic flow. This scheme generates corrected forms for the approximate nonlinear differential equations, the boundary conditions and the pressure-velocity-potential relations. It has to date been used only for steady flow. Time-dependent terms were added, on a consistent basis, to the various formulas in question. A one-dimensional unsteady flow situation was examined, whose exact solution is known and which was believed to provide an opportunity for discriminating among the proposed approximations.

It is not felt appropriate to report here the details of the "mass flux" investigation, since most of them became available only after the grant termination date of March 31, 1979.

List of Project Publications

1. Summa, J.M., "Potential Flow about Impulsively Started Rotors," J. Aircraft, Vol. 13, No. 4, April 1976, pp. 317-319.

2. Summa, J.M., "Unsteady Potential Flow about Wings and Rotors Started Impulsively from Rest," in Kinney, Ed., Unsteady Aerodynamics, Proceedings of a Symposium Held at University of Arizona, March 1975, Vol. II, pp. 741-767.

3. Johnson, E.H., Rizzi, P., Segenreich, S.A., and Ashley, H., "Optimization of Continuous One-Dimensional Structures Under Steady Harmonic Excitation," AIAA Journal, Vol. 14, No. 12, Dec. 1976, pp. 1690-98 (originally appeared in Proceedings, AIAA/ASME/SAE 17th Structures, Structural Dynamics and Materials Conference, King of Prussia, Pa., May 5-7, 1976).

4. Rizzi, R., "Optimization of Multi-Constrained Structures Based on Optimzlity Criteria," Proceedings, AIAA/ASME/SAE 17th Structures Structural Dynamics and Materials Conference, King of Prussia, Pa., May 5-7, 1976 (expected to appear in J. Aircraft).

5. McIntosh, S.C., and Segenreich, S.A., "Weight Optimization Under Multiple Equality Constraints Using a Modified Optimzlity Criterion," presented at AIAA/ASME/SAE 17th Structures, Structural Dynamics and Materials Conference, King of Prussia, Pa., May 5-7, 1976.

6. Petre, A., and Ashley, H., "Drag Effects on Wing Flutter," J. Aircraft Vol. 13, No. 10, October 1976, pp. 755-763.

7. Ashley, H., and Petre, A., "Fluturarea de Incovòiere-Rasucire la Aripi Drepte in Domeniu Incompresibil cu Considerarea Fortelor Aerodinamice ca Forte Urmaritoare," Buletinul Institutului Politechnic Bucuresti, Seria Mecanica, Vol. XL, No. 4, 1976, pp. 61-74.

8. Boyd, W.N., "Effect of Chordwise Forces and Deformation and Deformation Due to Steady Lift on Wing Flutter," Proceedings AIAA/ASME/ASCE/AHS 20th Structures, Structural Dynamics and Materials Conference, Vol. II, April 1979, (submitted for publication in J. Aircraft).

9. Ashley, H., "Some Contributions to Aerodynamic Theory for Vertical Axis Wind Turbines," Proceedings of the 12th Intersociety Energy Conversion Engineering Conference, Vol. 2, pp. 1624-1632, Washington, D.C., Aug/Sept. 1977, now published in Journal of Energy, Vol. 2, No. 2, March/April 1978, pp. 113-119.

10. Ashley, H., "Use of Asymptotic Methods in Vibration Analysis," Wind Turbine Structural Dynamics, NASA Conf. Publication 2034, DOE Publication CONF-771148, Workshop held at Lewis Research Center, Nov. 1977, pp. 39-52.

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